Transient Hollow Cathode Effects and Z pinch Formation in a High Current Capillary Discharge with a Metal Plasma

Edmund S. Wyndham, Mario Favre, Raúl Aliaga Rossel, Hernán Chuaqui, Ian Mitchell, Jorge S. Díaz, and Alvaro Pernas
Facultad de Física, Pontificia Universidad Católica de Chile, Casilla 306, Santiago 22, Chile.
(Dated: July 2004)

The results from a series of experiments are presented whose purpose is to explore different schemes which may lead to the formation of pure metal plasmas in a capillary discharge with parameters appropriate for X ray lasing. The experiments were performed in ceramic wall capillary discharges at currents of up to 120 kA, with an available ID of between 3 and 8 mm and with lengths from 60 to 100 mm. Initial plasma conditions in the capillary exploit transient hollow cathode effects in a preionizing discharge. A laser focussed onto the back surface of the cathode initiates both beam activity in the capillary volume and plasma injection. To promote metal ablation into the pinch channel of elements other than the ceramic wall material, a number of graded ring schemes have been tried. The plasma is observed axially using both time and energy resolved soft X-ray pin hole images as well as from time resolved soft X-ray spectra. By varying the rate of rise of the current of the main discharge, and the preionizing conditions the diameter and the stability of the Z-pinch column are seen to be affected. The ratio of the species from the ablated wall material to the plasma formed from the graded ring structure is found to depend both on the capillary dimensions as well as the other operating conditions.

INTRODUCTION

The capillary discharge has lately been the object of much experimental research with the observation of lasing in a Ne-like Argon plasma [1]. Even discharges using stored driver energies of ~0.1J have been shown to be very bright sources of nanosecond soft X-ray radiation in submillimeter diameter plasmas. The importance of well collimated transient electron beams generated by using a hollow cathode, HC, geometry has shown to be of key importance [2] in the pulsed or THCD (transient HC discharge) mode. The variety of high density and hot plasmas has so far been limited to ablating wall material or using an initial filling gas. The purpose of the present work is to attempt the formation of metal plasmas in capillaries of up to 10 cm in length. Electron beams emanating from the HC are essential to produce the initial pinch conditions in the capillary. In a previous work [3] the properties of a plasma generated in a 6 cm smooth bore alumina capillary were presented. Using the same generator and incorporating a series of metal rings along the length of the tube, a significant fraction of metal plasma has been produced in discharges from 6 to 11 cm in length and n several geometries of tube and ring structure. In all cases no initial filling gas is present.

DESCRIPTION OF THE EXPERIMENT

The capillary is mounted as the load of a small switched line coaxial pulsed power generator, GEPOPU, which allows pulses to 150 kA in a nominal 120 ns pulse at $3\cdot 10^{12}$ A/s. If the line switch is shorted the capillary load may switch the current and this mode allows a slower value of the current rise, dI/dt, of $1,5\cdot 10^{12}$ A/s. A small peaking gap between the line and the load allows the application of a preionizing voltage of up to 20kV via a resistor to allow a preionizing current of ~100A. A pulsed Nd:YAG laser focussed onto a Ti bar in the hollow cathode volume generates a plasma which injects e-beams into the capillary volume, whose potential difference falls immediately to ~800 V. The pulsed power pulse is applied between 10 and 80 μs later. In addition to the usual voltage and current monitors, PIN diodes, a combined XRD and Faraday cup, time resolved energy resolved pinhole images and soft X-ray spectra in the range of 30 to 300 A using a Rowland Circle grazing incidence spectrometer.

Experiments Performed and Results

An initial experiment was performed using a 6 cm alumina tube with a 5 mm ID in which eight Ti rings of 2.8 mm ID which are placed equidistantly. In Fig. 1 we compare the pinhole images and the spectra between the discharge in capillaries with and without rings. The gross temporal X-ray emission and current trace remain unchanged, but substantial differences are seen in the spectra. It is immediately obvious that the prominent O VI lines in the smooth

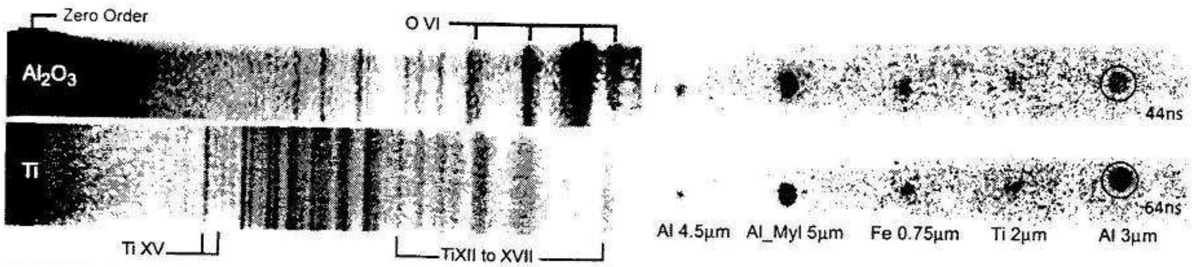

FIG. 1: Left. Upper: spectrum obtained in 5mm ID simple Al tube compared with , lower, a discharge using Ti rings with a 2.8 mm ID. Right. Two sets of 5 ns exposure filtered soft X-ray pinhole images taken at 44 and 64 ns into the current pulse. The outline of the available diameter for the plasma is shown as a circle.

bore alumina capillary are entirely absent in the Ti ring capillary. A number of; additional lines are visible in the Ti ring spectrum, and many of these may be ascribed to Ti lines. Those not assigned to Ti are other stages of Al. Limitations of the resolution of the spectrometer do not allow a definitive assignment of a considerable number of lines as many TiXII lines are very close to Al VI to Al VIII lines. A series of filtered pinholes are shown at two instants during the increasing current period of the discharge in the Ti ring geometry. The images indicate that the shorter wavelength radiation comes from a central core of the Z pinch. Some instabilities are evident from the Ti image, but they are less marked than in longer discharges or those of larger ID. Further to this geometry, discharges were performed in an 8 mm ID alumina tube with 3.8 mm ID Ti rings. These discharges are notably less stable.

In Fig. 2 we present current, e-beam, soft X-ray activity and pinhole images taken in an 11 cm capillary discharge. Eight Ti rings are placed equidistantly allowing a plasma channel of 2.9 mm. For these longer discharges the capillary self switches after about 50 ns of e-beam activity. The e-beam activity starts with a burst of irregular and decaying amplitude and terminates with a larger pulse which ends when the discharge current has attained about 10 kA. During this period of build up of activity in the hollow cathode, the tube holds the full 150kV of the applied line voltage with a current of order 1 kA. The current rise time is considerably slower than would be expected with the increased load inductance of the capillary. Simulation of the load current using a SPICE code indicates the dominant effect is that of an increasing conductivity of the plasma during the 80 ns following the initiation of the main current conduction. A further condition for operation is that plasma must penetrate from the laser spark into the capillary volume and this requires at least 20μs. The pinhole images are not as tight as the 6 cm discharge and their intensity is reduced.

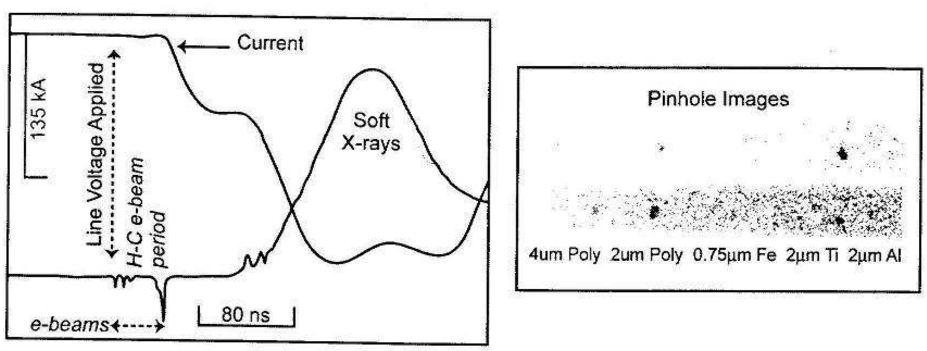

FIG. 2: Left. Upper: Current trace in 11 cm discharge, sowing self switching of capillary after hollow cathode beam period has terminated; lower, electron beams and soft X-ray emission. Right. Two sets of 5 ns exposure filtered soft X-ray pinhole images taken at 80 and 100 ns into the current pulse.

Figure 3 shows part of the spectrum obtained, between 35 and 150 Å, for the long capillary discharge. The two images show the differences in the species present when preionizing is present or not. When not present the laser plasma expands freely into the capillary; the external electric field is only applied when the main line voltage is applied. In the region between 59 and 93 Å a number of Al and Ti lines coincide, but inspite of this a number of assignments may be attempted. The ionization stages present can be estimated very approximately by using a CRE model such as FLY [4]. This code, however, only models pure plasmas and Li-like and higher stages of ionization. While Al VIII and IX stages are present, the most intense lines, marked '(p)' of the NIST tables are notable for their weakness. The ionization stages present as a function of temperature and density and the expected spectrum remain

unknown for mixes of arbitrary concentrations of Al, Ti and O. Al XI stages are barely detectable, as are Al VI. Al VII may be clearly identified at 93.3 Å. A group of Ti XII lines is seen at 59 Åin the case of no preionization. It is, however, easier to assign lines outside the range mentioned. At shorter wavelengths, where the spectrometer rapidly loses sensitivity, a number of Ti XIII and XV resonance lines may be seen in the second order. At longer wavelengths these stages as well as Ti XII to XIV have a considerable number of intense lines where only aluminium transitions of Al IV to VI are significant, and the plasma is substantially hotter than we would expect for emission of Al IV and A1 V.

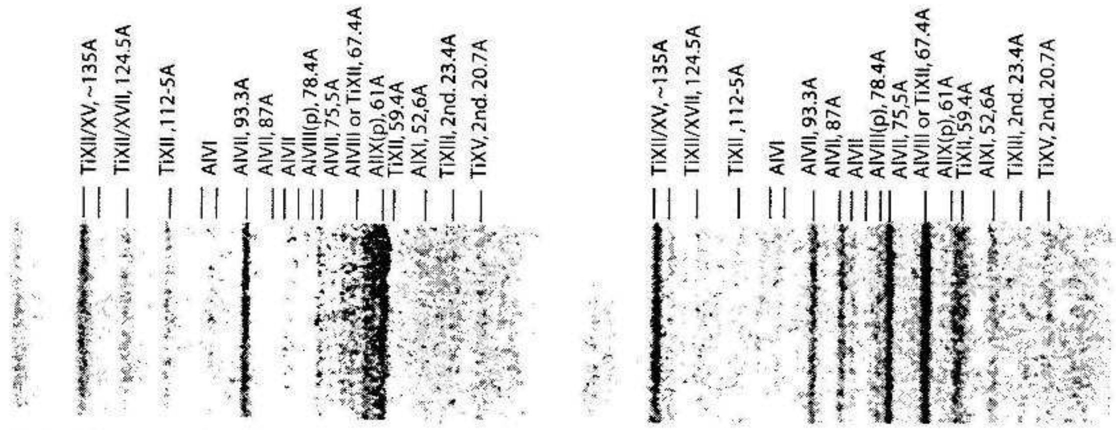

FIG. 3: Spectra taken in 11 cm discharge comparing the effect of (left) prionizing current on and (right) preionizing current off.

DISCUSSION

The plasma instabilities are less severe for the smaller of the two tube diameters. Instabilities are consistent with a rather wider range ionization stages in coexistance than for a single temperature plasma. While the THCD injected plasma is sufficient to provide a low impedance Z-pinch channel at 6 cm length, the longer discharge is limited in X-ray emission by the significantly lower current density. Work is required to increase the plasma injection and beam intensity from THCD, as is theoretical modeling to allow the precise composition of the plasma from the spectra. Work is presently under way to produce pure Ti plasmas, in the absence of other elements.

ACKNOWLEDGEMENTS

We gratefully acknowledge funding from the ANDES Foundation C-13768 and FONDECYT 1030968, both Chilean institutions, the former private and the latter public.

[1] Smirnov, V.P., and Mesyats, G., Phys. Rev. Letters 65, 2503-2504 (1994).